Mitigation of Thermal Threats Using Devices Based On Shape Memory Alloys

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Abstract

Shape Memory Alloys (SMAs) have commonly been used in the design of mitigation measures for thermal threats. An SMA typically undergoes large dimensional changes when heated through its transition temperature, the transition occurs over a relatively small temperature range and this temperature range can be selected by choice of SMA composition. In addition, some SMAs have good mechanical properties. This combination of properties leads to possibilities for the design of mitigation devices that can be tailored to activate at any chosen temperature and to operate independently of heating rate. They are thus equally suitable for meeting slow and fast heating threats.

QinetiQ has been investigating two types of SMA based mitigation device:

The first is a threaded joint of which one component is constructed of an SMA. The joint is capable of carrying the necessary shear loads, but when it is heated the thread disengages, giving rise to a vent in the munition casing. Aspects considered are the shear strength of such joints, the long term stability of the SMAs, their use in conjunction with various metals and the various compatibility issues that arise.

The second is based on SMA wire, which is easy to procure and into which 'memory' is easily imparted by controlled stretching. When such wire is wound on to the munition which is subsequently exposed to the thermal threat, it can exert a very considerable force which can case the casing to rupture by a variety of mechanisms. Such devices are potentially retrofittable to a range of rocket motor and warhead cases.

Applications are discussed for both types of device.

1. Introduction

Thermal threats represent a significant part of the overall Insensitive Munitions (IM) threat scenario. For guided missiles powered by solid propellant rocket motors, an item of major concern is the rocket motor itself because a) it contains by far the largest amount of energetic material and b) it presents a large area to any potential threat. However, the thermal threat to warheads is also of concern.

Some types of rocket motor case construction, notably composite and steel strip laminate, are reasonably effective against in fast heating situations, e.g. fuel fires, because the strength of the motor case reduces very significantly so that it does not allow the rapid pressure build-up that leads to a high order explosive event. However, mitigating against slow heating has remained a more intractable problem. Slow heating is both very hazardous and difficult to combat because, a) after slow heating, the Temperature of Ignition (T of I) of the propellant decreases, b) the propellant becomes more sensitive and c) because of the slow heating rate the whole weapon assumes a more or less uniform temperature. Thus very few types of motor case construction will weaken significantly before the propellant T of I (which may be as low as 125^{o}C for double base propellants) is reached. At the same time, it will be apparent that to perform its normal function as a motor case it needs to retain its structural integrity up to at least 80^{o}C.

This leads to the desirability of having a separate venting device that can not only reduce the severity of the response but also reduce the degree of propulsiveness. Ideally it should operate before the T of I is reached and should be independent of heating rate. It is an advantage if the device does not introduce additional energetic materials that may introduce new hazards (i.e. be passive). Further advantages would accrue if the device were relatively cheap and retrofittable to existing weapons. This paper describes a number of devices based on shape memory alloys (SMAs) that appear to be capable of achieving most if not all these objectives.

2. Venting Techniques

There are a number of venting techniques that have been proposed over the years. Two of them are briefly mentioned below.

The first is the 'shear vent patch strip' (refs 1, 2) which uses a patch adhesively bonded to a motor case. The patch has a different coefficient of thermal expansion to that of the case so that shear stresses build up in the adhesive as the case is heated. This eventually leads to a shear failure in the adhesive which causes the patch to detach and uncover a vent. Shape memory alloys can also perform this function, and would probably give a more controllable activation temperature.

There have been a number of proposals for using low melting alloys or polymers that, on melting, release a steel circlip or other retention device (refs 3-6). These low melting materials have relatively poor mechanical properties, even when cold, and usually lose strength over a temperature range of tens of degrees. They cannot therefore be used as part of the case structure but are deployed indirectly, to allow a structural component to move and thus release the confinement.

3. Venting Techniques Using Shape Memory Alloys

Mitigation devices based on Shape Memory Alloys (SMAs) are particularly attractive because:

a) They transform from one metallurgical state to another, within a relatively small range of temperature.

b) Significant dimensional changes are associated with this change.

c) Comparatively large forces can be exerted if the dimensional change is resisted.

d) There is sufficient choice of alloys that exhibit shape memory effects to allow the activation temperature of the device to be selected accurately.

Mitigation devices based on shape memory alloys are not entirely new, and some of the more promising ones found in the literature are briefly mentioned below.

The US Navy has patented a device (refs 7, 8) for disengaging an end of a rocket motor case when heated. It uses a closure piece with a ring of steel or aluminium alloy prongs, each with an outward facing lip. When the device is assembled, the lips then engage with an internal step in the rocket motor case. A ring of Ti-Ni SMA is placed around the ring of prongs. When it contracts, due to the increasing temperature arising from the thermal threat, it forces the prongs inwards causing them to disengage from the lip in the motor case. A number of 2.75 inch motors are being built and tested using this device.

Saab-Bofors Defence has patented a device for releasing the nozzle of a rocket motor (ref 9). A ring of SMA is placed within the joint between the motor case and the rocket nozzle. When the rear end of the rocket motor is heated, the SMA ring contracts and disengages the two components.

Bayern Chemie Protac has patented a family of devices that use SMA collars that expand when heated to break a component of a rocket motor joint (ref 10). This component is usually notched to provide a stress concentration.

A Thiokol patent (ref 11) describes the embedding of wires of SMA in the composite during manufacture. When heated the SMA wires bend and disrupt the internal structure of the composite, causing it to lose most of its strength. It is only suitable for venting composite rocket motor or warhead cases.

4. QinetiQ Devices Based on Shape Memory Alloys

Work carried out in QinetiQ over the period 2002 to 2005 has concentrated on two types of venting device:

a) The disengaging threaded joint, of which one component is a SMA, and

b) The cutting or buckling of rocket motor and warhead cases using contracting SMA wire.

Both are described below, but to date most success has been achieved with the second of these.

4.1 Disengaging Threaded Joint

In designing a mitigation device of this kind there is a choice between an internal SMA connecting ring externally threaded and contracting when heated and an external SMA ring internally threaded and expanding when heated. The former has commonality with the conventional use of SMAs as shrink tubes and is easier to achieve. However, a rocket motor that uses a cartridge loaded charge usually requires a smooth internal profile. Consequently it was decided to pursue the latter, more difficult option.

For the concept to work it is necessary to demonstrate four things:

1. Satisfactory means of procuring rings of the required dimensions and imparting the 'memory' by hoop compression.
2. Sufficient thread strength in the low temperature, martensitic, state.
3. Enough radial movement for the thread to disengage on heating the ring, and for this to occur within the desired temperature 'window'.
4. That compatibility issues (e.g. galvanic corrosion between dissimilar metals, mismatch of thermal expansion coefficients, etc.) can be overcome.

The first of these has proved difficult, but small rings, of around 40 mm diameter have been procured and 'memory' imparted by swaging through die. For larger tubes, a source of Ti-Ni alloy sheet has been identified and such sheets would be large enough to produce any desired size of ring by wrapping and welding. Electron beam welding trials have also been carried out successfully on this material. These studies are progressing.

Some measurements of the shear properties of Ti-Ni alloys have been carried out by Manchester University, and the results suggest that adequate thread strength should be achievable. However, a more serious limitation is presented by the relatively low Young's modulus of Ti-Ni in the martensitic state (about 30 GPa). For many applications, this would prevent a normal ISO thread form being used as there is a tendency for the joint to spring apart due the radial component of the reactive force on the inclined surfaces of the thread, so that buttress thread may be required. Figure 1 illustrates the difference between the two types of thread form.

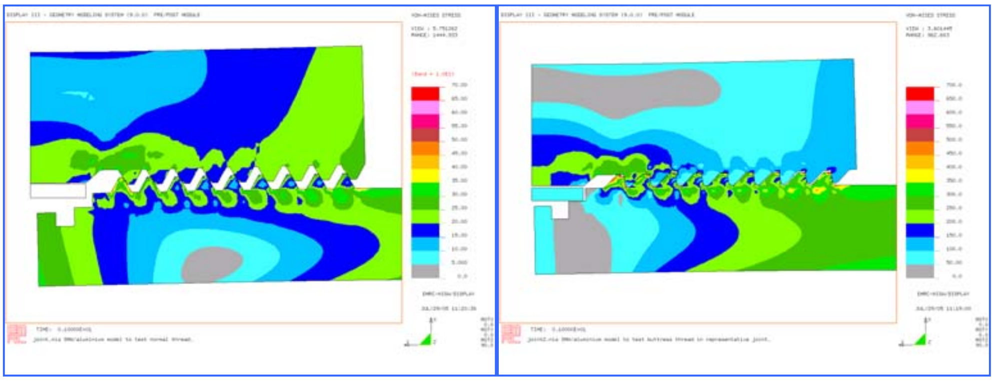

Figure 1: Elastic-plastic FE model of a) a standard ISO thread and b) an equivalent buttress thread. It is evident that the IOS thread has a strong tendency to spring apart under load, whereas the buttress thread largely avoids this.

There seems, however, little doubt that the recovery strain of the SMA when heated is sufficient to disengage either form of joint. Figure 2 shows the results obtained on a set of short rods into which 'memory' had previously been imparted by longitudinal compression. Upon heating, it is evident that recovery strains of the order of 5% are achievable. It also shows that the phase transition occurs over a small temperature range, in this case of the order of 5°C.

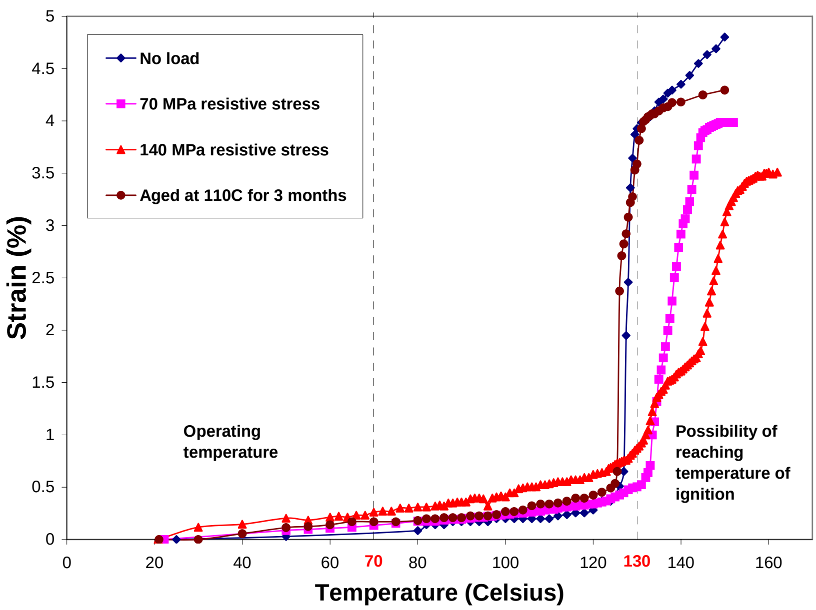

Figure 2: Results of strain recovery tests on short Ti Ni rods upon heating

Some of the tests were carried out with a resistive load. As can be seen from figure 2, this has the effect of reducing the recovery stain and increasing the temperature at which the phase change takes place. For the purposes of the disengaging threaded joint concept, this last point is not normally significant.

For a 100 mm diameter ring with an internal thread of depth 2 mm a 4% recovery strain would be sufficient for full disengagement. In fact, for the purposes of venting, about half this would be sufficient because a partially disengaged thread is unstable and it would tend to release on one side significantly reducing the joint strength.

The devices described employ different metals in close proximity to each other, so there are a number of compatibility issues to be addressed.

- Galvanic corrosion
- Stress corrosion
- Coefficient of thermal expansion (CTE) mismatch

Galvanic corrosion can be countered by suitable coatings and the use of sealants to exclude fluids that might act as electrolytes. None of the components are under sufficient long term stress for stress corrosion to be an issue. The CTE mismatch of Ti-Ni in comparison with steel and aluminium alloy is large enough to have to be taken into account but is not a 'showstopper'.

NIMIC (NATO Insensitive Munitions Information Centre), now MSIAC (Munitions Safety Information and Analysis Centre) has raised a query over the long term dimensional stability of SMAs in general under heat soak and thermal cycling. This would be of concern because the SMA threaded ring is part of an engineering assembly that might tighten up or loosen during the service life of the munition. Consequently, a series of precision measurements has been undertaken to ascertain whether a significant problem exists. Both heat soak and thermal cycling tests were carried out with measurements taken in a temperature controlled room on specimens withdrawn at intervals. It is concluded that a small effect exists, but that it is of the order of normal engineering tolerances. Most of the change takes place in the first few days or cycles, so if tighter tolerances were needed a SMA component could be stabilised by a preliminary heat treatment.

4.2 Cutting and Buckling Devices Based on Shape Memory Alloys

The original idea behind this concept was that SMA wire, which is readily procured, would first have 'memory' imparted into it by a stretching operation. It would then be wound on to the rocket motor or warhead casing on top of a series of cutting edges. When heated, the SMA wire would contract and drive the cutters into the casing as shown schematically in figure 3.

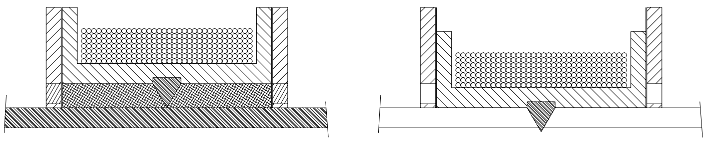

Figure 3: Schematic diagram showing cutters being driven into a rocket motor case by the contraction of SMA wire

The initial tests along these lines did not use cutters but relied on the sharp edges of the channel carrying the wire to penetrate the tube. However, these tests tended to result in the tube buckling (but not to the extent that it split) rather than being cut and the temperature at which the device activated was unexpectedly high (150°C); much higher than the 70°C claimed by the wire supplier. It was also apparent at the time that there was nothing in the literature on shape memory alloys to provide guidance as to the best way of imparting memory into the wire, what winding tension to use and how much wire to use.

It was evident from this that in order to arrive at anything like an optimised design for a cutting device it would be necessary to develop some basic property data for SMA wire. It was also evident that the use of cutters would increase the chances of cutting the tubes. It was therefore concluded that it would also be necessary to test several types of cutter and, for each of these, to measure the force and stroke needed to cut the various types of tube that were of interest.

The first step in this plan was to measure the stress-strain relationships for wires stretched (to impart 'memory') at a variety of loads. These tests were carried out in a testing machine and the results are shown in figure 4.

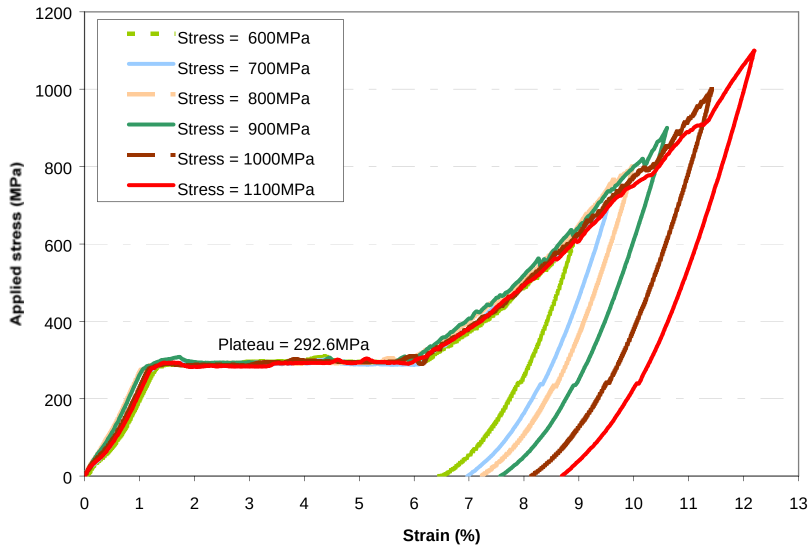

Figure 4: Stress-strain curves measured for Ti Ni SMA wire in a standard tensile testing machine

The behaviour is highly non-linear, with a long 'plateau' followed by a stage that is similar to work hardening. The behaviour is also non-linear upon unloading. Subsequent experiments on the various wire samples were used to measure the strain recovery upon heating. As expected, there is a trend for the recovery strain to increase with the peak applied load but it levels out at around 1000 MPa. At the largest applied load used (1100 MPa) it was noticed that occasional wire breaks occurred, so it was decided to standardise on an applied load of 1000 MPa for the remainder of the programme.

Given that in a cutting device the cutters meet considerable resistance as they drive into the tube, it is clear that some resistive force will be transmitted to the contracting wire. The next step was thus to measure how the wire behaves as it contracts against a load. The results for a series of tests using different resistive stresses are shown in figure 5.

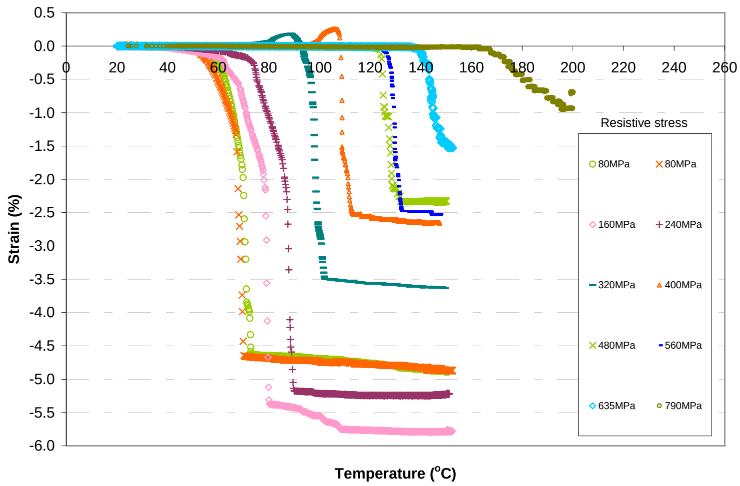

Figure 5: Set of test results for Ti Ni wire contracting against various resistive stresses

It can be seen from this that as the resistive load increases the recovery strain reduces and the transition temperature increases. These results explain how it was possible for the device tested in the earlier studies to activate at a temperature as high as 150°C. Evidently the resistive force was very large in these early tests. The importance of figure 5 is that it encapsulates much of the information needed for designing devices driven by SMA wire. In particular it shows that it is possible to 'fine tune' the activation temperature of a device by controlling the stress that the contracting wire has to work against.

The other information needed is the force and displacement needed to cut tubes of various materials. Tests on this were carried out under both uni-axial and bi-axial compression. The results of these tests are summarised below:

Tube material	Thickness (mm)	Cutting force (Nmm^{-1})
7010 Aluminium alloy	0.7	118
±75° CFRP	1.365	75
±75° GRP	1.774	100

From the data contained in figure 5 and the results of the cutting tests it was possible to proceed with the design of cutting devices. The starting point is to select the desired activation temperature of the device (obviously dependent on the maximum service temperature and the T of I of the propellant or explosive). The working stress of the SMA wire to give this transition temperature is then read off from figure 5. The amount of wire to use in relation to the stiffness of the tube to be cut can then be calculated.

Figure 6 shows a device fitted to a NLAW (MBT-LAW) flight motor case which consists of an aluminium alloy tube overwound with aramid. Three different types of cutter were used and it is evident that one of them was more effective than the others. This device activated at 125°C.

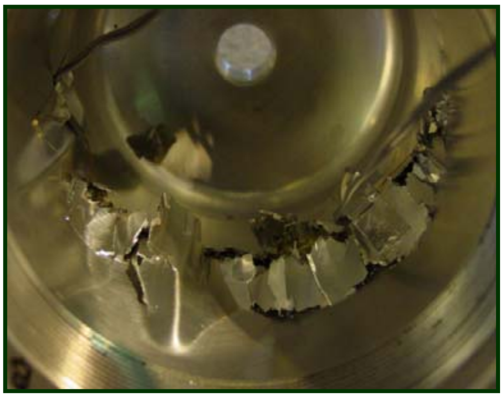

Figure 6: Successful demonstration of a cutting device on a NLAW flight motor case

The extent of the cut produced and the weakening around the remainder of the circumference would be sufficient to achieve the necessary degree of venting, but there is little doubt that a full circumferential cut could have been achieved if the optimum cutter had been used throughout.

For a tube-launched weapon such as NLAW, given that a circumferential cut has been produced in the rocket motor case, by an SMA device or otherwise, it may well be desirable to bring about more complete venting by cutting the lauch tube at an adjacent position. In general, cutting composite tubes, such as CFRP and GRP, is considerably easier than cutting a ductile metal such as an aluminium alloy. Figure 7 shows a complete circumferential cut on a GRP tube achieved using a similar device.

Figure 7: Cutting of a 100 mm diameter GRP tube

For some weapons, cutting the launch lube alone would provide a worthwhile amount of mitigation. A case in point is the MLRS/GMLRS rocket pod container shown in figure 8. Thus in the present design, a burning reaction (which is the planned IM response) in the rocket motor is likely to cause flame to be propagated forwards into the payload. For the bomblet versions of these weapons, the centre core burster can then react and distribute armed bomblets over a wide area. With the unitary warhead this type of event is a lesser but still significant hazard. If the launch tube can be cut somewhere in the section forward of the rocket motor but aft of the payload bay, then the flame can be vented sideways and the reaction of the payload prevented. A difficulty with fitting a venting device to the MLRS/GMLRS tubes is the limited space available between the tubes.

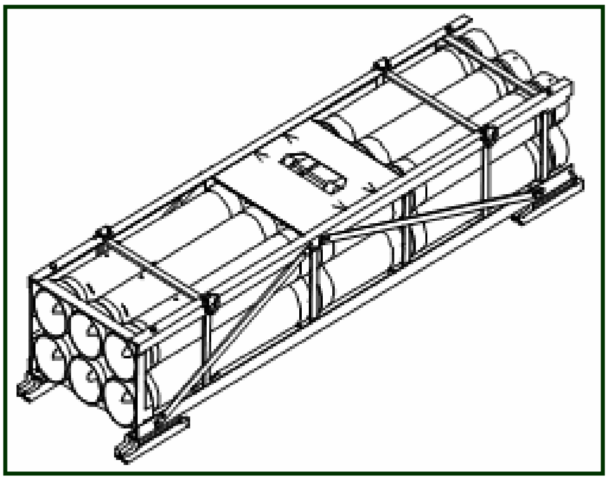

Figure 8: The MLRS/GMLRS Rocket pod container (RPC)

However, calculations show that a scaled up version of the device shown in figure 7 would be sufficiently compact to fit into the space.

Another difficulty is that it is not feasible to remove the tubes from the RPC in order to wind on a device of this kind. The QinetiQ team is currently working on a method of retro-fitting a set of cutters driven by contracting SMA wire without the need to remove the tubes from the RPC. The device would produce a cut extending around about 80% of the circumference, which is judged to be more than sufficient for venting purposes. This vent can be produced in any desired direction (probably outwards). It should be noted that such a device could be activated by ohmic heating of the SMA wire and hence be used as the basis of semi-active venting.

It was recognised at an early stage that it was unlikely that sufficiently hard cutters would be found to cut the types of high strength steel used for rocket motor cases. Consequently, for steels, the alternative approach was followed of attempting to buckle the tube, with the hope that this would lead to cracking. This approach has worked well for a steel strip laminate tube, as shown in figure 10.

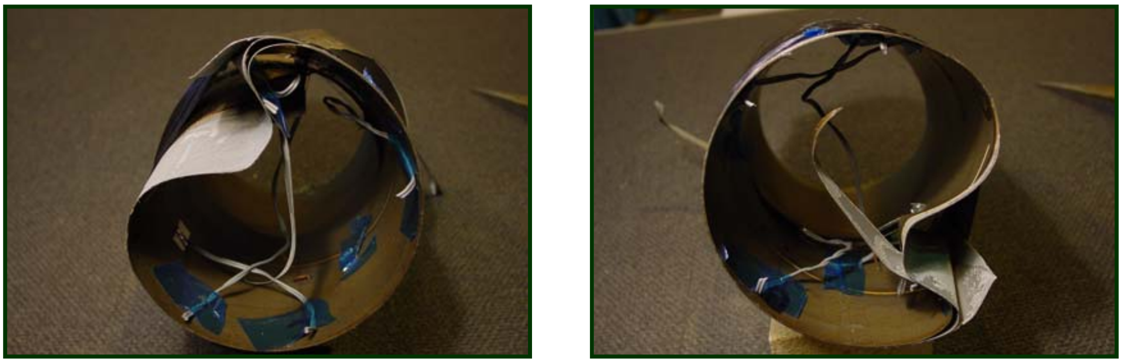

Figure 10: A buckled and cracked section of a steel strip laminate rocket motor case

It is evident that this tube had collapsed with such violence as to crack the steel strip (2 GPa tensile strength). Actual rocket motor cases of this construction have end rings. These may well assist in the production of a large vent by providing a discontinuity that enhances the difference between the buckled and non-buckled regions.

The next step in this programme will be to attempt to buckle and crack a monolithic steel rocket motor case. Calculation suggests that buckling will be relatively easily achieved. The crucial issues are whether one or more sharp lobes can be produced and whether the radius of curvature will be small enough to lead to cracking.

5. Conclusions

A number of SMA based devices for passive mitigation of thermal threats have been described. Some of these would have to be designed into the munition from the start but others have considerable potential for retro-fitting to legacy weapons. In the case of rocket motors, as well as reducing the response category, they would considerably reduce the propulsiveness.

Depending on the application, most of the devices would be vulnerable to being triggered prematurely by internal or external heating. However, the insulation needed to counter this need only be applied in the immediate vicinity of the device, not over the complete surface of the munition.

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